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TITLE: A COMPARISON BETWEEN AN SCR AND A VACUUM INTERRUPTER SYSTEM FOR REPETITIVE OPENING

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# A COMPARISON BETWEEN AN SCR AND A VACUUM INTERRUPTER SYSTEM FOR REPETITIVE OPENING*

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## ABSTRACT

Two conceptual systems are analyzed for repetitive interruption of current from an inductive energy storage source. The interruption level for both systems is 25 kA at 25 kV. Factors such as interruption frequency, power dissipation, reliability, maintenance, developmental time, and cost are compared.

The vacuum interrupter system is considered feasible for an interruption frequency of 25 Hz and a 10-20% duty cycle. Five millisecond output pulses deliver 78 MW to a one ohm load with a voltage rise time of less than one microsecond. Hardware costs are less than $100,000 for the system, and development time is one year.

The SCR system is considered feasible for an interruption frequency of up to 10 kHz. A series spark gap connected to the load limits the otherwise continuous duty factor. Fifteen microsecond output pulses deliver 94 MW to a one ohm load with a voltage rise time of less than one microsecond. Hardware costs for the system exceed $1,000,000 and development time is 2 to 3 years.

## INTRODUCTION

Interruption of direct current from an inductive store can be accomplished by either of two methods. One method involves creating an arc voltage which is greater than the product of the current and the load impedence. Fuses, explosive interrupters, and conventional dc circuit

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breakers operate on this principle. The second method involves creating an artificial current zero by injecting an equal but opposite current through the interrupter. This process is known as commutation and is used in the two conceptual systems described here.

Both of the systems utilize a similar interruption circuit, the primary difference being the interrupters. In one case this interrupter is a series-parallel array of 1260 fast switching SCRS, and in the other case the interrupter is a series array of two, seven-inch vacuum interrupters. For sake of comparison, both interrupters are designed for use at 25 kA and 25 kV, although either system could be designed for higher or lower currents or voltages. This paper will examine potential differences in operating frequency, cost, reliability, lifetime, power dissipation, and development time.

## 1. Background

The Los Alamos National Laboratory has been involved in switchgear development for fusion experiments since 1974.[1] At that time one interrupter test facility rated at 10 kA continuous current, 25 kA pulsed current, and 60 kV recovery voltage was constructed to test switches for inductive energy storage systems. Presently three test facilities are operative, the largest rated at 100 kA steady-state current, 280 kA pulsed current, and 120 kV recovery voltage.[2]

In addition to basic research, Los Alamos has been actively involved in switch testing and development for the national fusion community. During 1978, a system was developed using Westinghouse interrupters for use in the Tokamak Fusion Test Reactor at Princeton.[3] Over 1000 consecutive interruptions were performed at 25 kA and 25 kV. A system designed by Toshiba was also tested over 1000 times for the same application.[3] An experimental General Electric interrupter was tested up to 112 kA using a Los Alamos designed and constructed actuator. In 1979, a 25 kA steady-state interrupting system was designed by Los Alamos and Oak Ridge for use in the Large Coil Project.[4] This system is now being tested and will be used to interrupt current in six superconducting magnets which store as much as 200 MJ each. A 50 kA steady-state interrupting system is presently being designed for interrupting current in a superconducting magnetic energy system at Los Alamos for the Tokamak Poloidal Field System program.

## 2. Basic Interrupting Circuit Using Commutation

A schematic of a repetitive interrupting circuit using commutation is shown in Fig. 1. The circuit breaker represents an array of either SCRs or vacuum interrupters and the load will be considered to be a one ohm resistor. The following initial conditions are assumed.

1. The circuit breaker and bypass switch are closed and the power supply has charged the storage inductor to 25 kA.
2. The commutation capacitor is precharged to 25 kV with the polarity shown.
3. The energy stored in the inductor is much greater than the energy delivered to the load.

To begin the sequence, the bypass switch opens transferring all the current into the closed circuit breaker. If the circuit breaker is a vacuum interrupter, its contacts then open. The commutation SCRs labeled "A" are now triggered. This discharges the commutation capacitor through the circuit breaker in a direction opposite to the inductor current. When a net current zero is created in the circuit breaker, interruption occurs. The inductor current now flows through the still conducting

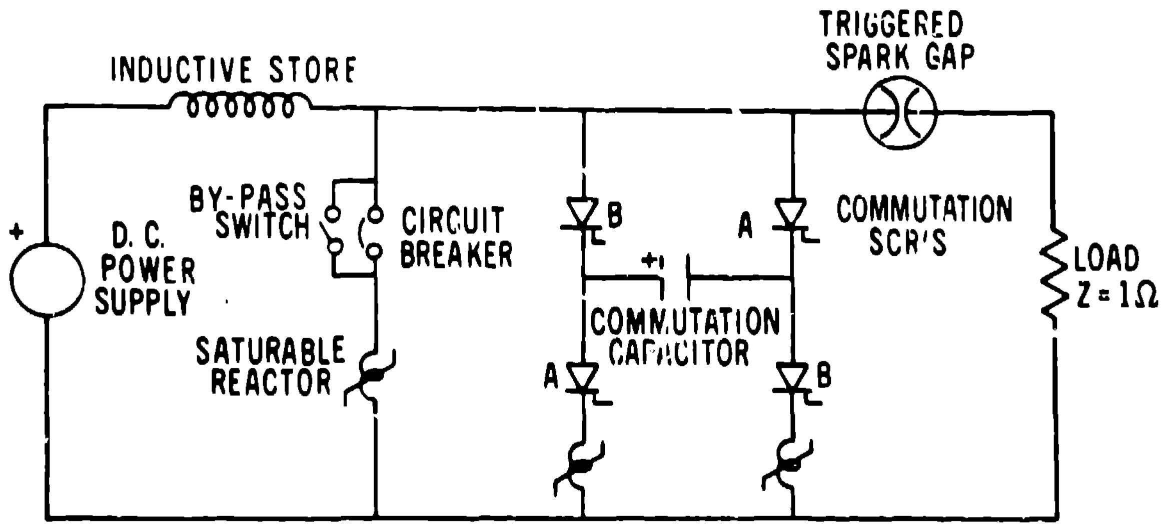


Fig. 1. Repetitive switching circuit.

commutation SCRs, "A", and begins to recharge the commutation capacitor in the opposite direction. When this capacitor voltage reaches slightly over 25 kV, the triggered spark gap closes. This produces a high rate of voltage rise on the load. The full inductor current now flows into the load creating a maximum voltage of 25 kV. Because the commutation capacitor was charged to slightly over 25 kV, a reverse voltage appears across the commutation SCRs, and allows them to recover. To begin a new cycle, the circuit breaker recloses, and the triggered spark gap recovers. The sequence is now repeated except that commutation SCRs, "B", are used this time due to the reverse charge on the commutation capacitor. On the third sequence, SCRs, "A", will be used because the capacitor will be forward charged after the second sequence. Thus, SCRs, "A", are used on odd numbered interruptions and SCRs, "B", are used on even numbered interruptions.

The primary difference in the interrupting circuit when using vacuum interrupters or SCRs is the commutation capacitor. Because the SCRs have a longer turn-off time than the vacuum interrupters, a larger capacitor is required to hold the recovery voltage negative after current zero. The commutation SCRs for the SCR interrupter circuit must also be larger, but this is a result of the higher operating frequency rather than differences in the nature of the circuit breaker used. These details will be examined below.

## 3. The Vacuum Interrupter as a Circuit Breaker

Figure 2 is a schematic of the vacuum interrupter assembly used as a circuit breaker in the interrupting circuit of Fig. 1. The breaker consists of two Westinghouse WL-33552 commercial interrupters connected in series. The axial field coils maintain a diffuse discharge during arcing in the interelectrode gap and increase the interruption ratings significantly. Similar interrupters have been tested at Los Alamos with currents in excess of 40 kA and voltages in excess of 30 kV simultaneously on a single interrupter.[5] Toshiba has developed a vacuum interrupter which can interrupt 100 kA at 12 kV.[6] The use of two interrupters in series provides a conservative design for high reliability as demonstrated on two similar systems tested for use in

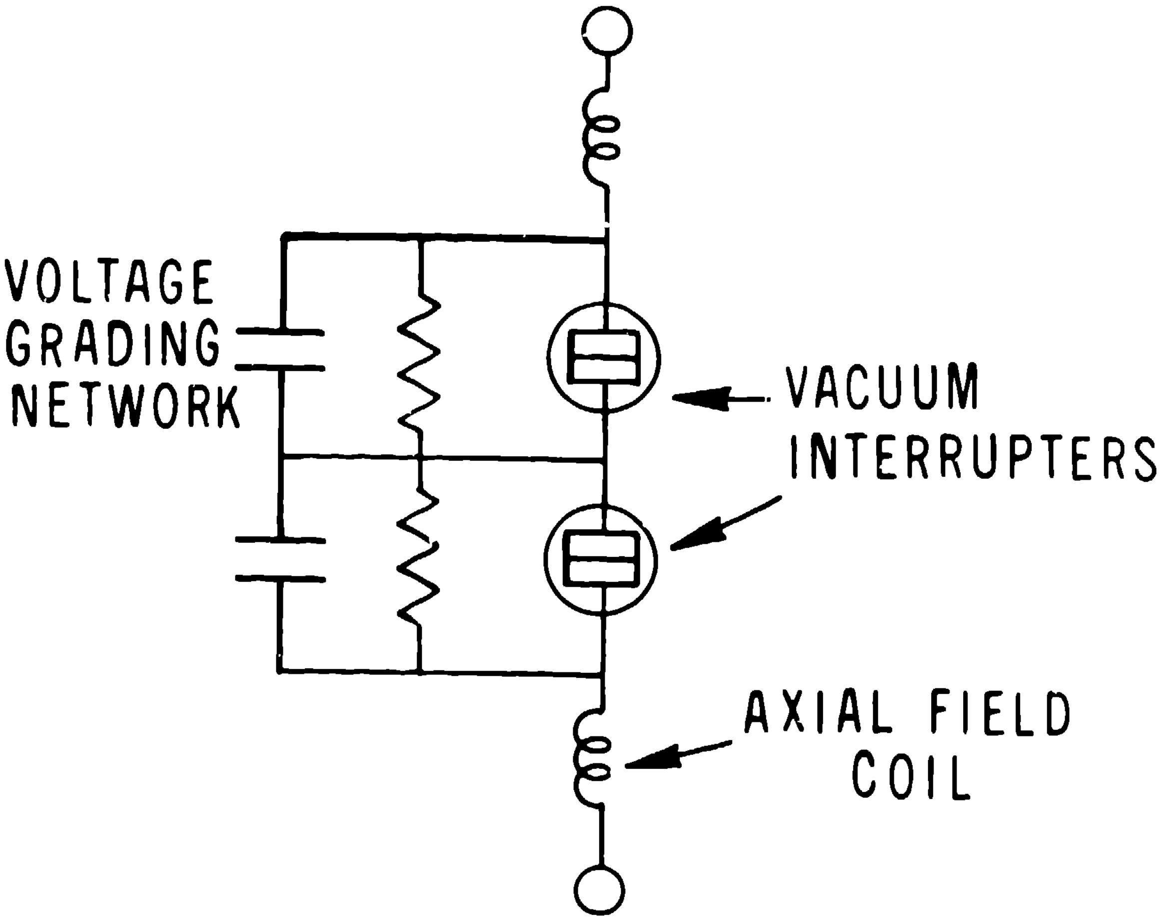


Fig. 2. 25 kA 25 kV vacuum circuit breaker.

TFTR.[3] Estimated contact lifetime for these interrupters is 5000 to 10,000 operations at 25 kA.

The normal steady-state current rating for these interrupters is 2 kA. Los Alamos and Westinghouse have been jointly developing an interrupter with water-cooled stems and contacts over the past several years. The first prototype conducted 10 kA on a continuous basis. A second prototype with an improved electrode-stem design and a special actuator designed at Los Alamos is being prepared for testing. It is designed to carry 25 kA on a continuous basis and would eliminate the need for the external bypass switch shown in Fig. 1. Both options, however, will be discussed in this section.

3.1 Operating Frequency

Commercial actuators for vacuum interrupters are not designed to operate at high repetition rates. Typical mechanical opening times range from 5 to 10 ms and reclosing times vary from 40 to 1000 ms. A special actuator for use at high frequencies would have to be developed. Figure 3 details a conceptual 25 Hz actuator with a motor driven camshaft to operate the linkage of a vacuum interrupter. Table I lists some technical information on design parameters for this device. Besides the

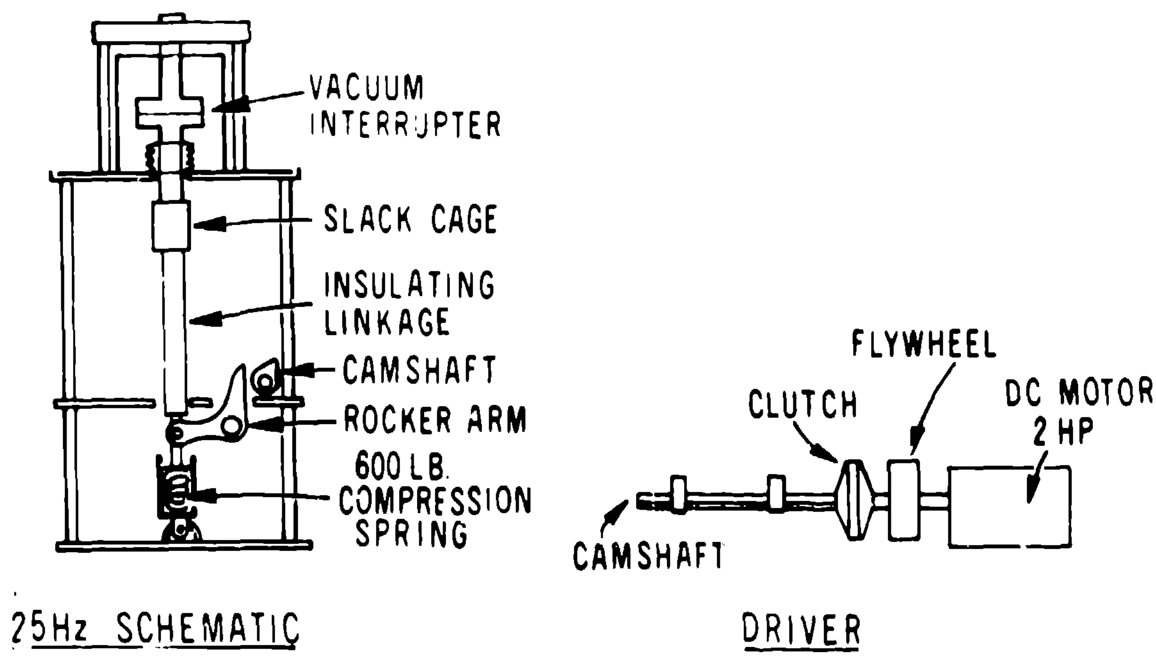


Fig. 3. 25 Hz Actuator.

TABLE I

25 Hz ACTUATOR DETAILS

| | |
|---|---|
| Operating frequency, Hz | 25 |
| Opening time, ms | 5 |
| Reclosing time, ms | 5 |
| Time in closed position, ms/cycle | 30 |
| Mechanical power at 25 Hz, HP/interrupter | 0.86 |
| Motor speed, rpm | 1500 |

inherent synchronization in this type of design, the array is easily expandable to include more series or parallel interrupters.

Typical waveforms showing the circuit breaker current, $I_{CB}$, the commutation capacitor voltage, $V_{CC}$, and the voltage on a one ohm load are pictured in Fig. 4. The load voltage duration could be extended to as long as 35 ms by camshaft design or shortened to as little as 2 to 3 ms by increasing the force of the return spring. Transient current and voltage stresses on the interrupter during this sequence are discussed in Section 3.3.

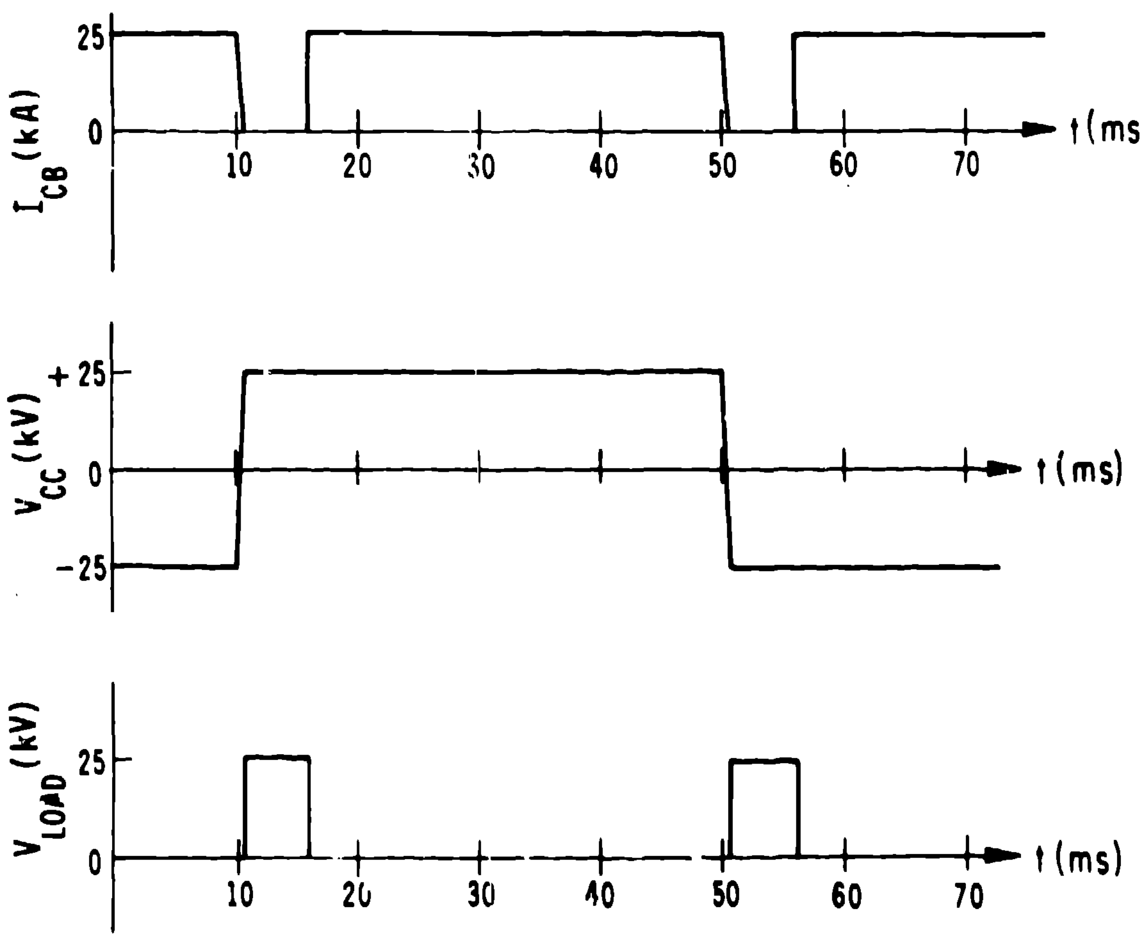


Fig. 4. Current and voltage waveforms for vacuum interrupter system.

3.2 Power Dissipation

Slightly over 3 kJ are generated by the vacuum arc prior to each interruption resulting in a total of 78 kW power consumption at 25 Hz. This energy must be removed from the device. Commercial interrupters are designed to dissipate an average power of only 30 to 60 W during normal conduction at 2 kA. However, their inherent thermal mass is sufficient to absorb the power generated by 25 Hz interruption for about 2 s. The interrupter must be allowed to cool for 30 to 60 min before the sequence could be repeated. The latest water cooled interrupter is designed to remove a maximum of about 20 kW heat loading from the contact region. It would only have to cool for 10 to 20 s between interruption sequences. Either the water-cooled interrupter system or the combined bypass switch and commercial interrupter system generate less than 10 kw dissipation during conduction in the closed state.

The triggered spark gap envisioned for the 25 Hz system is a General Electric rod-array vacuum spark gap. These gaps have been very successful in laboratory testing[7] and have an extremely low voltage drop during conduction. The estimated lifetime at 25 Hz and 25 kA is over $10^5$ operations. The 25 Hz power dissipation of the spark gap is also about 80 kW and limits its continuous operation. The inherent thermal mass would allow about 5 to 10 s of continuous duty before cooling becomes necessary. A water-cooled spark gap for a higher duty factor would be recommended if used in conjunction with a water-cooled interrupter.

The SCR commutation switches used in the 25 Hz vacuum interrupter system dissipate a negligible amount of energy. Thus, the total dissipation of the system at a 25 Hz interruption rate is 0.16 MW. The power delivered to the load during this same sequence is 78 MW.

3.3 Interrupter Stresses

The electrical stresses on the individual vacuum interrupters are conservative enough to insure a reliability of greater than 99%. In power systems, these interrupters face peak voltages of 22 kV with a rate of rise of recovery voltage (RRRV) in excess of 25 kV/μs. In the 25 Hz system, the peak interrupter voltage is 12.5 kV with an RRRV of only 700 V/μs. Due to these unusually low voltage stresses, a commutation rate of 1 kA/μs can be utilized while still maintaining a high degree of reliability.

## 4. The SCR as a Circuit Breaker

Figure 5 is a schematic of the SCR circuit used as a breaker in the interrupting circuit of Fig. 1. The breaker consists of 30 parallel connected arrays of 42 SCRs in series.[8] This circuit has a continuous current rating of 30 kA at a maximum voltage of 50 kV. The 10 kHz switching rate used in this analysis dissipates more energy than a steady-state current of 25 kA. As a result, the 30 kA continuous system must be derated to 25 kA at 10 kHz. Peak voltage ratings that are a

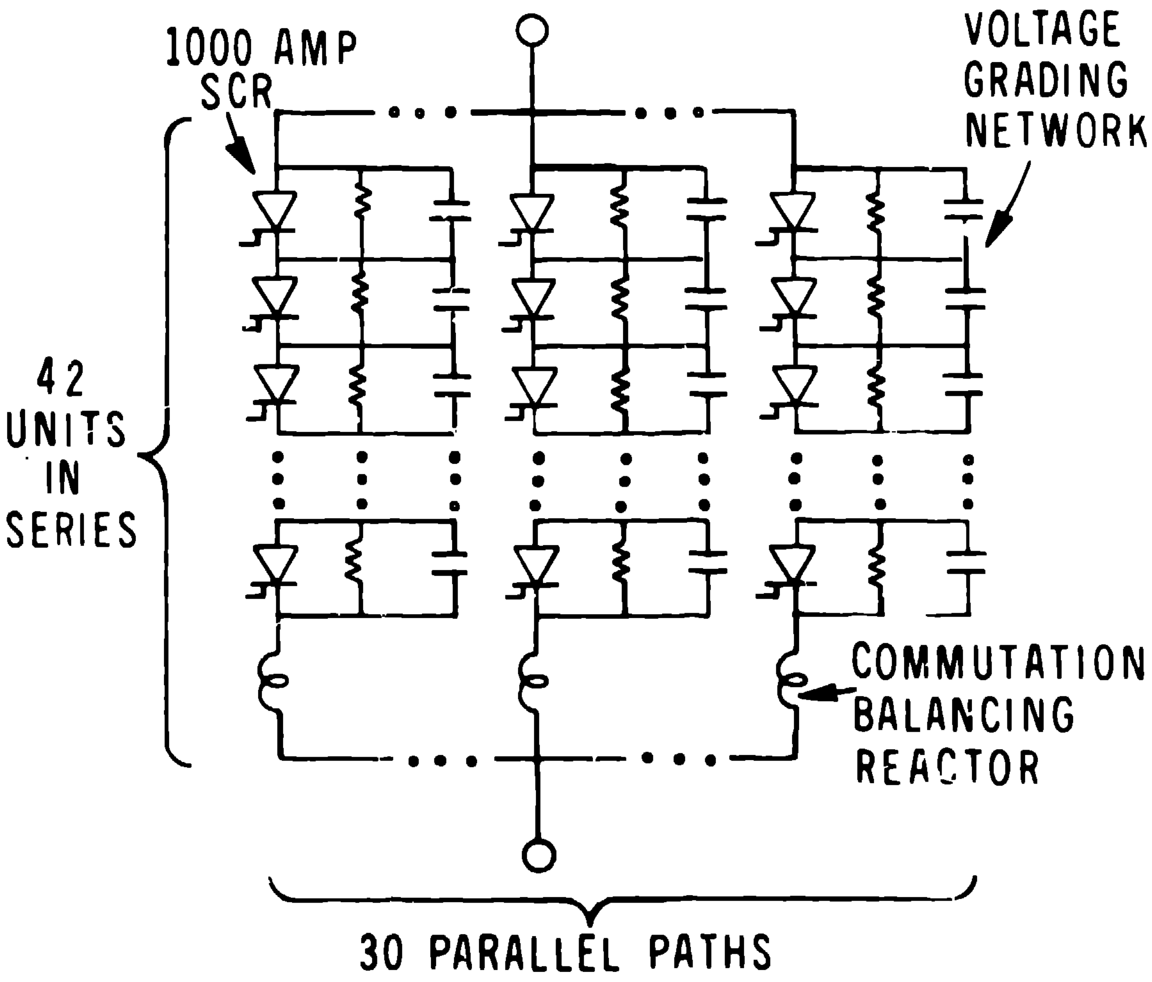


Fig. 5. 25 kA 25 kV SCR circuit breaker.

factor of two above normal operating voltages are quite common in semiconductor systems.

4.1 Operating Frequency

The operating frequency selected for this analysis was chosen as half the maximum operating frequency for the particular SCR used. The SCR was selected on the basis of highest current and voltage ratings for a 20 μs turn-off device. The fast turn-off time is necessary to minimize the size and weight of the commutation capacitor.

Typical waveforms showing the circuit breaker current, $I_{CB}$, the commutation capacitor voltage, $V_{CC}$, and the voltage on a one ohm load are pictured in Fig. 6. The load voltage duration could be extended to as long as 35 μs by decreasing the conduction time of the interrupter array

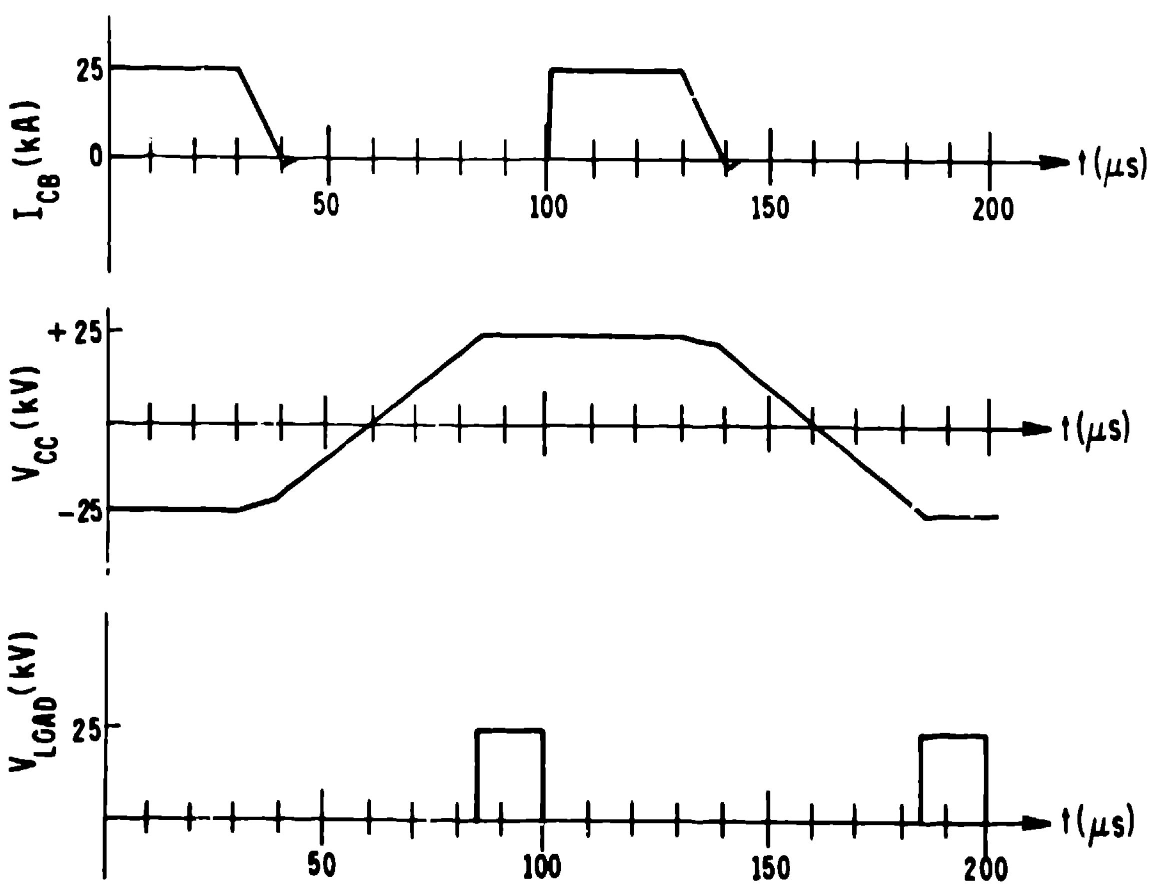


Fig. 6. Current and voltage waveforms for SCR interrupter system.

and shortened indefinitely by increasing the conduction time. Switching stresses are discussed in Section 4.3.

### 4.2 Power Dissipation

According to published data,[9] power consumption of the SCR array conducting 35 μs wide pulses at 10 kHz is 1.9 MW. Steady-state conduction losses amount to 1.6 MW. Obviously, a parallel bypass switch would be necessary during inductor charging or when no interruption sequence is required. The commutation SCRs consume even more energy than the primary interrupter. Approximately 2.5 MW are consumed by the commutation SCRs at 10 kHz. If the same spark gap used with the vacuum interrupter system is used with the SCR system, 0.94 MW would be dissipated. Thus, the total power used by the SCR system at 10 kHz is 5.4 MW. The power delivered to the load during the same time is 94 MW. Everything in this system could be run continuously except the spark gap. Another SCR array could be substituted for the spark gap for continuous operation, but the 1 μs voltage risetime would require a prohibitively large number of SCRs if the published ratings were followed. Transient overrating tests could be conducted to reduce the size of this array.

### 4.3 Interruption Stresses

The electrical stresses on the SCR interrupter were chosen within the published ratings to insure a high degree of system reliability. A comparison between the published maximum ratings[9] and the actual operating stresses is shown in Table II.

TABLE II

MAXIMUM RATINGS VERSUS OPERATING STRESSES FOR INDIVIDUAL SCRs

| | Maximum Ratings | Operating Stresses |
|---|---|---|
| Peak voltage, V | 1200 | 600 |
| Average current, A | 1000 | 833 |
| Peak di/dt, A/μs | 200 | 100 |
| Turn-off time, μs | 20 | 20 |
| Peak dv/dt, V/μs | 400 | 24 |
| Maximum frequency, kHz | 20 | 10 |

The dv/dt stresses are unusually low due to the large parallel commutation capacitor required for the 20 μs turn-off time.

## 5. Systems Comparison and Conclusions

In general, the SCR interrupter system is capable of high frequencies, short output pulses, and continuous operation. It is also an expensive system and would require 2 to 3 yr to develop fully. The vacuum interrupter system is a low frequency, long output pulse, intermittent duty system. It is comparatively inexpensive and the technology is well developed. The required development time is about one year. Table III compares the two systems in more detail.

Both systems appear to be technically feasible with present state-of-the-art devices. Light triggered thyristor technology is advancing rapidly and would be especially useful in these systems, especially if

TABLE III

COMPARISON BETWEEN THE VACUUM AND SCR INTERRUPTER SYSTEMS RATED AT 25 kA AND 25 kV

| | Vacuum Interrupter | SCR |
|---|---|---|
| Operating frequency, Hz | 25 | 10,000 |
| Output pulse width, μs | 3,000-35,000 | 1-35 |
| Maximum duty factor, % | 10-20 | 100[a] |
| Commutation capacitor, μF | 17.5 | 24.2 |
| Power dissipation during interruption, MW | 0.16 | 5.4 |
| Power delivered to load, MW | 78 | 94 |
| Cost for interrupter alone, $ $(10)^3$ | 25 | 500[b] |
| Cost for commutation network, $ $(10)^3$ | 45[b] | 500[b] |
| Reliability, % | > 99 | > 99 |
| Number of interruptions between maintenance, $(10)^3$ | 5-10 | > 100[c] |

[a]Continuous duty spark gap/SCR is utilized.

[b]SCR cost at $200 each plus $200/SCR for gate circuitry, grading networks, and mounting assemblies.

[c]SCR array is used instead of spark gap.

turn-off times could be reduced. Actuator development for the vacuum interrupter system is believed to be minimal at the 25 Hz level described.

## REFERENCES


[1] C. E. Swannack, R. A. Haarman, J. D. G. Lindsay, and D. M. Weldon, "HVDC Interrupter Experiments for Large Magnetic Energy Transfer and Storage (METS) Systems," Proc. 6th Symp. Eng. Problems of Fusion Res., San Diego, CA, Nov. 18-21, 1975; IEEE Pub. No. 75CH 1097-5 NPS, 662, (1976).

[2] W. M. Parsons, E. M. Honig, and R. W. Warren, "A 33-GVA Interrupter Test Facility," Proc. 2nd IEEE International Pulsed Power Conference, Lubbock, TX, June 12-14, 1979.

[3] R. W. Warren, W. M. Parsons, E. M. Honig, and J. D. G. Lindsay, "Tests of Vacuum Interrupters for the Tokamak Fusion Test Reactor," Informal report LA-7759-MS, April 1979.

[4] W. M. Parsons and R. J. Wood, "Protection Circuits for Superconducting Magnets," Proc. 4th ANS Topical meeting on Tech. of Controlled Nuc. Fusion, King of Prussia, PA, Oct. 14-17, 1980.

[5] R. W. Warren and E. M. Honig, "The Use of Vacuum Interrupters at Very High Currents," Proc. 13th Pulse Power Modulator Sym., Buffalo, NY, June 20-22, 1978.

[6] S. Yanabu, E. Kaneko, H. Okumura, and T. Aiyoshi, "Novel Electrode Structure of Vacuum Interrupter and Its Practical Application," Proc. IEEE PES Summer Mts., Minneapolis, MN, July 13-18, 1980, IEEE No. 80SM700-5.

[7] C. P. Goudy, General Electric Research and Development Center, personal communication.

[8] Westinghouse Model T9GH121062DH

[9] J. F. Donlon and W. H. Karstaedt, Westinghouse Fast Switching SCR Data Book, Westinghouse Electric Corp., 1978.